ICT-MobileSummit 2009 Conference Proceedings
Paul Cunningham and Miriam Cunningham (Eds)
IIMC International Information Management Corporation, 2009
ISBN: 978-1-905824-12-0

Simulation framework for performance evaluation of RF antenna combining systems

Michael WICKERT[1], Uwe MAYER[1], Ralf EICKHOFF[1], Frank ELLINGER[1], Jesús IBANEZ[2], Ignacio SANTAMARÍA[2]
[1]*Technische Universitaet, 01069, Dresden, Germany*
Tel: +49 351 463 33919, Fax: + 49 351 463 38736, Email: michael.wickert@tu-dresden.de
[2]*Communications Eng. Department, University of Cantabria, 39005 Santander, Spain,*
Tel: +34 942 201552, Fax: + 34 942 201488, Email: nacho@gtas.dicom.unican.es

Abstract: Several methods of low-cost analogue radio frequency (RF) antenna combining system utilizing spatial diversity have been proposed recently. This paper presents a simulation framework for evaluation of those systems capable of performing specification, evaluation and optimization tasks, while all RF impairments that could result from the analogue front-end can be simulated. By means of the analysis of one exemplary system architecture for 5 GHz wireless local area networks (WLAN) using spatial diversity the application of this framework is validated at a reasonable trade-off between accuracy and required processing time. Furthermore, the effect of forward compensation of the weighting errors introduced by the nonlinearities of one circuit component is studied by means of this framework. Because the achieved reduction of the error vector magnitude (EVM) in the studied test case is only 1.2 dB, it is concluded that this weight-compensation can be left out.

Keywords: Spatial diversity, Spectre, MIMO, EVM, beam forming, channel modelling

1. Introduction

Facing high costs and long cycle times in fabrication of radio frequency circuits and components, simulations are a cost effective method to predict performance of individual circuits up to complex systems. Furthermore, possible issues, which may arise when functional blocks are connected together, shall be detected prior to setting up an expensive measurement scenario, since connecting components together in order to build a system is more complex and time-consuming, than simply establishing the physical interconnect [1]. Especially when considering multiple antennas to improve data rate and coverage range of data links in recently proposed multiple-input multiple-output (MIMO) applications, the architectural decision is eased, if clear performance data is available.

For instance the existing simulation environment used in [2] performs block level simulations very time-efficiently. However, a careful and hence time-consuming examination of the correct model parameters has to be conducted prior to successful application of those systems. Furthermore, the flexibility to investigate the impact of changes at circuit level on system performance metrics is very poor.

This paper presents a simulation framework, which is used to verify, evaluate and optimize the performance of antenna combining systems. It utilizes broadly available software for the different computation tasks. Since this framework operates directly on the designed circuits it offers highest possible flexibility, while keeping the required processing power at a low to moderate level. The requirements to simulation tools in terms of powerful and efficient equation solving, versatility, accuracy and user friendliness are met.

2. RF combining architecture

The system evaluated with the simulation framework is part of the MIMAX project described in [3]. The main novelty of this approach is the ability of using spatial diversity, while keeping system complexity and power consumption at a minimum by performing the weighting operation at RF. From the use of more than one antenna a spatial diversity gain can be used to increase the signal-to-noise-ratio (SNR) and hence reduces EVM of the combined signal. The algorithms for calculating the optimum weights from different amounts of channel information as well their theoretic performances are described in [5].

The detailed architecture of the RF part of this new MIMO concept designed in 0.25 µm SiGe BiCMOS is shown in Figure 1. It consists of four identical antenna front-ends each composed of a receiving (RX) and transmitting (TX) part. The TX is fed by the split up-converted data signal, while the four weighted received signals are added up in a combiner circuit. The core component performing the desired weighting operation at RF is the vector modulator (VM), which is found in the RX and TX-path, respectively. It performs a multiplication of the amplified antenna signal with a quasi-static complex weight determined by the MIMO algorithm giving a resulting phase shift range of 360° and an amplitude range of more than 20 dB. Overall eight vector modulators and hence, eight complex control signals are required, which are calculated in the digital processing part and transferred to the analogue front-end by a pad-saving SPI port. 16 digital to analogue converters (DACs) convert those values into specific control currents that are fed into the VMs.

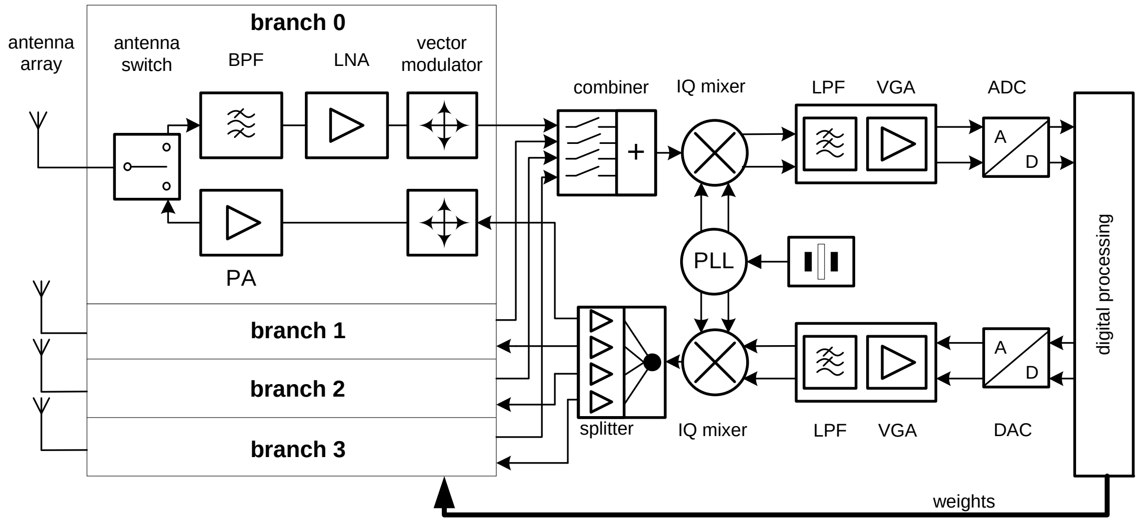

Figure 1: Analogue front-end architecture for RF antenna combining

3. Simulation framework

3.1 Framework structure with MATLAB and Spectre

Figure 2a depicts the principle of the simulation framework, which bases on a developed MATLAB environment encapsulating a Spectre co-simulation. MATLAB functions perform all tasks for signal generation, simulation control and data analysis, while the actual device-under-test (DUT) circuit is processed with the Spectre circuit simulator. A time consuming setup of co-simulations is avoided, because all settings for the circuit simulator are taken from the circuit design environment (Cadence) such as directory paths and model settings.

With this structure it is possible to apply any kind of signal generation, channel modelling and analysis, since the corresponding functions can be implemented in MATLAB. These functions mostly do not need to be reprogrammed, since they are already required during the system design process. Furthermore, impairments of other sub-systems, e.g. phase noise in the oscillator or back-off of the PA can be modelled [6].

The Spectre co-simulation can be controlled via OCEAN commands [7], which also form the interfaces between the MATLAB and Spectre simulations via data files located in the simulation directory.

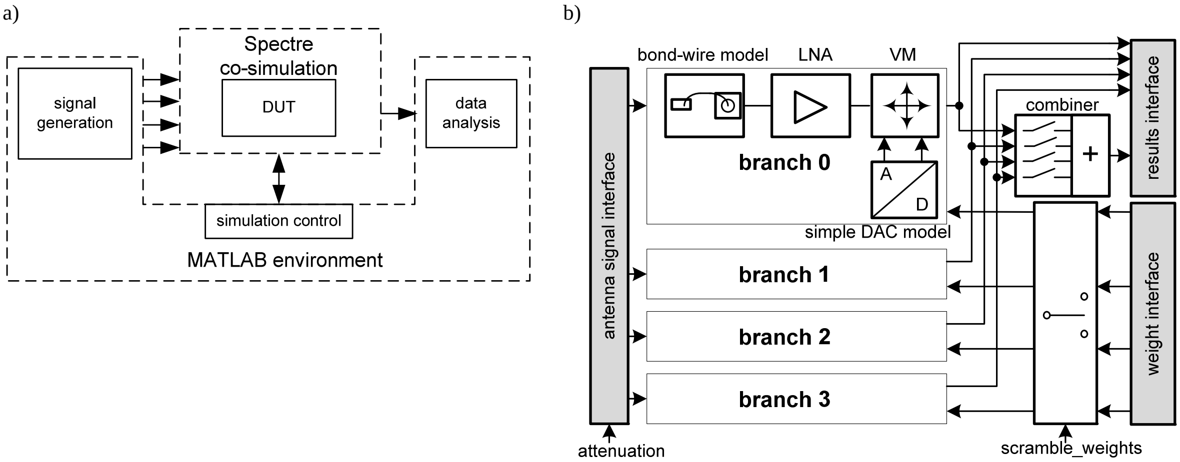

Figure 2: Simulation framework a) overview; b) simulated DUT

3.2 Application of the framework on a RF-combining architecture

The proposed simulation framework was applied to predict performance and evaluate the interoperation of the components of the WLAN transceiver architecture previously described. In order to maintain feasible processing times, simplifications of the operating conditions were conducted, if the resulting impact can be considered negligible.

A transient simulation of the whole analogue front-end system with a sufficient amount of data is impractical, because the complexity of the designed circuits is too high. Furthermore, some components are off-the-shelf, where only behavioural models can be derived from measurements. Therefore, the DUT circuit is reduced and only the most significant components in terms of RF-weighting performance are simulated by Spectre. The simulated DUT is depicted in Figure 2b.

The Zero-IF down-conversion mixer was not included in the system simulation, since its CMOS topology forces the time-steps of the simulation to very small values and hence increase overall simulation time drastically. For testing purposes, signals of the same power level and frequency range were applied to the input of the mixer and the resulting baseband signal did not show noticeable perturbations. A further reason, why simulations including the mixer component are considered impractical, can be found in the offset-cancellation loop, which is required in Zero-IF systems particularly prone to DC-offsets from self-mixing effects [1]. The very high time constants necessary in those loops for negligible symbol disturbance yield long settling times (>100 µs).

In order to generate a reproducible set of non-optimal weights a multiplication with an arbitrarily chosen fixed scramble matrix can be activated by a *scramble_weights* signal.

Quadrature amplitude modulation (QAM) in conjunction with a flat Rayleigh channel model is used in this environment, although the application uses orthogonal frequency division multiplexing (OFDM), where a flat channel model does not hold anymore.

However, in the final system compatible to the 802.11a standard [8] equalizers are employed to virtually create flat channel conditions for every sub-carrier, which is justified in this case, where only the impact from the RF circuits is studied. The 802.11a standard demands for -82 dBm antenna power, when operating 6 MBit/s with binary phase shift keying (BPSK). Here, QAM-16 with 20 Mb/s is used, because the project target is enhanced throughput at higher link radiuses. The maximum antenna power is normalized to a specified value P_S, while the other generated signals have lower power levels depending on the actual channel matrix. The size of this matrix is less than 4-by-4, since the transfer of only one data steam with exploitation of spatial diversity reduces the required rank.

The antennas of this system are considered by an effective gain and added noise level as part of the complex channel coefficients and overall channel noise.

The root raised cosine filters of the final scenario were implemented as RX and TX filters. Simple DAC models provide the required sign-magnitude description of the weights to the vector modulators. The sampling, synchronization and up/down-conversion blocks not shown here are considered ideal and hence do not alter the information of the signals.

A detailed illustration of the most relevant parts of the final simulation environment is given in Figure 3.

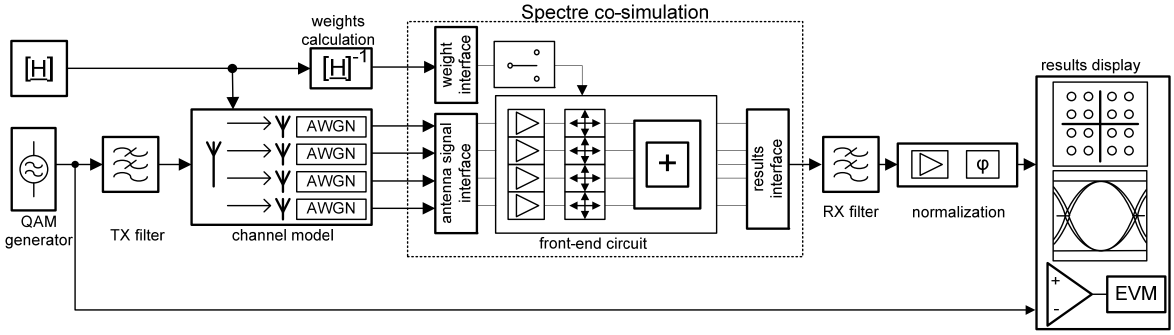

Figure 3: Applied simulation framework on a RF combining system

The obtained results are visualised by means of constellation and eye diagrams. However, the most significant performance metric for the simulated system part is the RMS EVM, since it represents influences from noisy devices and channels as well as nonlinearities in the circuits. The EVM is directly related to the expected SNR and bit error rate (BER) [9]. It is strongly determined by the synchronization and IQ correction functions that can be found in common receivers, which are typically carried out by the digital signal processing (DSP) part of the system. Here, those tasks are performed by corresponding MATLAB functions and the parameters for synchronization and IQ correction are tuned with respect to minimum EVM.

3.3 Simulation specific aspects

The design of individual circuit components is usually done using single or two-tone test cases, which can be solved by time saving harmonic balance (HB) or periodic steady state (PSS) simulations. However, for the purpose of realistic performance evaluation transient analysis is most fruitful [10]. If a system is to be analyzed with respect to its noise behaviour, standard linear noise computations can be used as long as the system can be treated as a linear. The simplest approach to simulate the influence of noise is to determine the small signal noise figure (NF) of the whole system and add a corresponding amount of noise to each of the inputs in the investigated frequency band. Figure 4 displays the spectrum of a generated test signal with P_S = -82 dBm and NF = 0 dB, which equals -102 dBm noise power in the 20 MHz band of interest at standard noise temperature.

If the noise influences the system in a more nonlinear way, these computations are not satisfactory anymore and simulation of noise in the time domain, called transient noise, becomes necessary [11]. Instead of adding a noise generator to the circuit's inputs, noise generators are added at device level [10]. The transient noise analysis, which is offered by the Virtuoso Mixed Mode Simulator 6.2, was unable to converge, even with strongly reduced tolerance settings for the front-end circuit. However, the simulation of individual building blocks was possible with an increase in computation time by a factor of 10. Thus, transient noise was only used to validate the small signal noise parameters with the power levels of the test signals for individual building blocks.

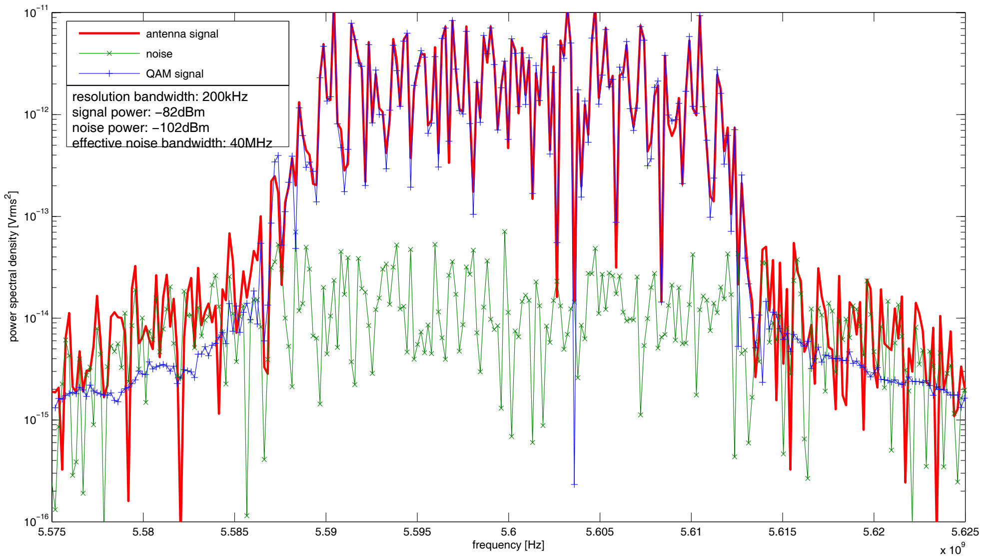

Figure 4: Generated noise and signal spectrum

Due to filtering and required settling times of the DUT the actual required simulation time is longer than the accumulated symbol duration. Although a sampling rate f_{Sample} of 50 GS/s is sufficient to describe signals with carrier frequencies $f_{Carrier}$ of 5.6 GHz, the Spectre simulation switches to smaller time-steps where necessary. Then, for data output an interpolation is needed to align the results back to 50 GS/sec. This introduces synchronisation problems yielding random phase shifts of up to

$$\Delta\varphi = \frac{2\pi f_{Carrier}}{f_{Sample}} \mathrel{\widehat{=}} 40°$$

Therefore the simulation time-step is set to a value (5 ps) that the simulation does not need to alter any further and signal interpolation is avoided at the expense of an increase in computation time.

4. Results

4.1 Performance of the simulation framework

The simulation results presented in the following were carried out on a simulation server consisting of eight AMD Opteron 64 Bit cores @ 2.4 GHz and 16 GBytes of RAM running a Scientific-Linux 4.4 operation system. The used version of Spectre is 5.10.41 USR4, while MATLAB2008a is employed. The DUTs complexity is 6000 nodes and 30000 equations for the circuit of Figure 2b and 10 000 nodes and 43000 equations for the front-end including the down-conversion mixer. The large number of equations yields the following processing times for 100 transferred symbols or 6 µs simulation time (Table 1).

Memory demand could be significantly reduced by enabling the saving of the output signals only. Thus the transient output files are smaller than 50 Mbytes and the allocated computation memory is only 200 Mbytes.

Table 1: Processing times for the simulation framework

	processing time	remarks
MATLAB	3 min	1st part (data generation)
Spectre	17 to 20 h	5 ps time-step
	6 : 30 h	20 ps time-step
	40 to 50 h	5 ps time-step with mixer
MATLAB	5 min	2nd part (data analysis)
MMSim6.2	200 h (estimated)	5 ps time-step, transient noise

4.2 Performance evaluation of the RF combining architecture

Including a safety margin of 3 dB in noise power the worst case scenario of the DUT is P_S = -82 dBm and NF = 8 dB. Other power levels and NFs were also simulated and the obtained EVMs are listed in Table 2. It is obvious that the weight scrambling matrix does not degrade every setting the same and there even exist weight sets that are not degraded at all. However, the EVM is strongly dependent on the cumulative signal power received by the antenna array, which in turn only depends on the actual channel matrix, while the noise level remains constant.

Table 2: Results for different power and noise settings
(The applied synchronization and normalization algorithms limit the EVM to appr. -35 dB)

NF [dB]	3	5	8	8
max. P_{Si} [dBm]	-82	-82	-82	-35
ΣP_{Si} [dBm]	-79.5	-77.3	-78.2	-31.5
EVM_{opt} [dB]	-16.6	-21.1	-17.2	-36
EVM_{scramb} [dB]	-4	-18.3	-14.8	-35

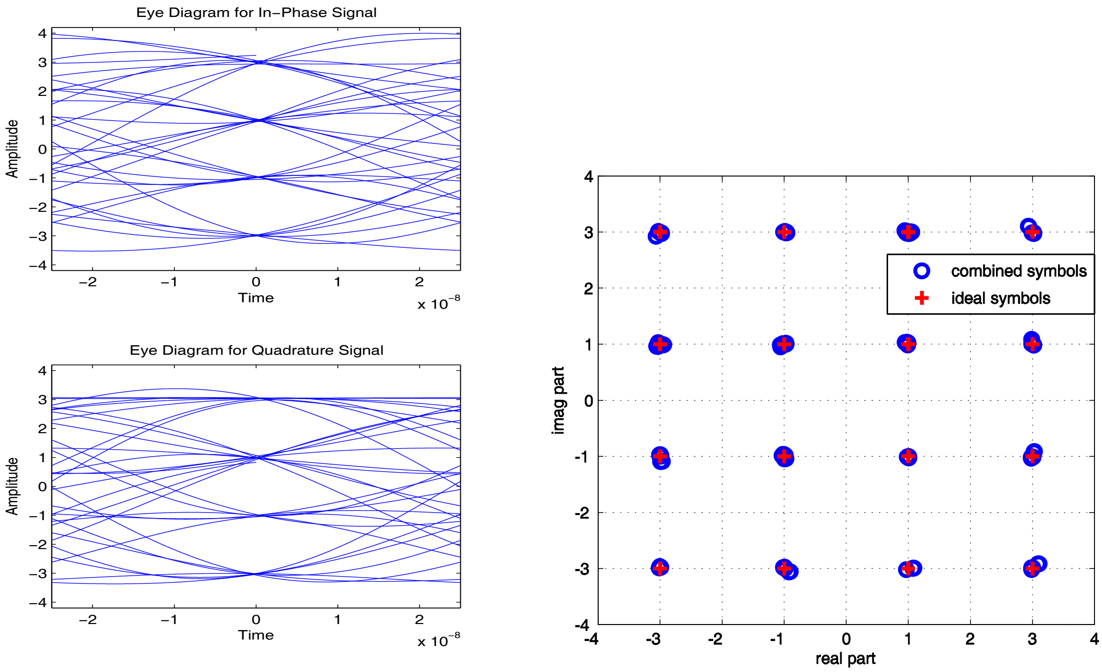

Figure 5: Eye and constellation diagram for P_S =-82 dBm without noise

The application of amplitude and phase shifters usually introduces unwanted phase and amplitude shifts. Therefore, the investigated MIMO architecture demands for forward error compensation of the weights. By means of the non-linear characteristics derived from the designed vector modulator (see Figure 6), the effect of two different methods to generate the correction factors is studied. The first one searches the complex mapping table for the smallest absolute weight error, while the second one uses high-order polynoms to interpolate real and imaginary mapping functions and inverts those functions performing a root-search. This is not to be confused with the error correction coding of the signals.

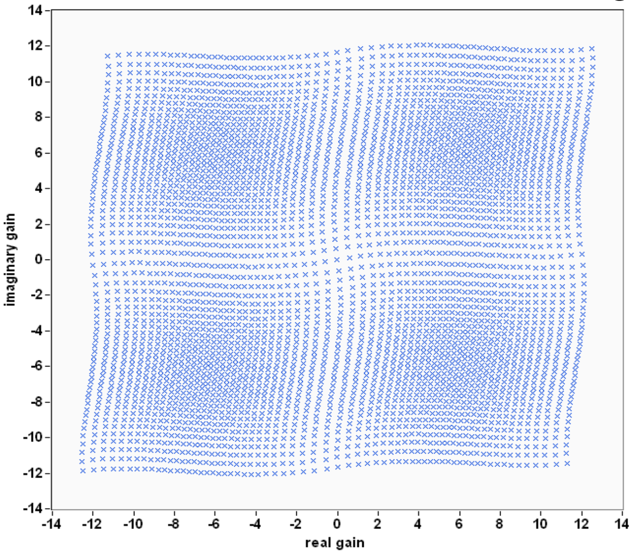

Figure 6: Simulated output vector space of the used VM with linear spaced control values

The exemplary response of the front-end on uncorrected and optimized weights is shown in Figure 7. It is observable that the difference in EVM is very small and the smallest constellation error is found for the weights calculated from the polynomial correction algorithms. The weight set obtained from the scrambling block of the DUT yields the constellation plot on the right, which clearly visualizes the potential risk of wrong weighting coefficients.

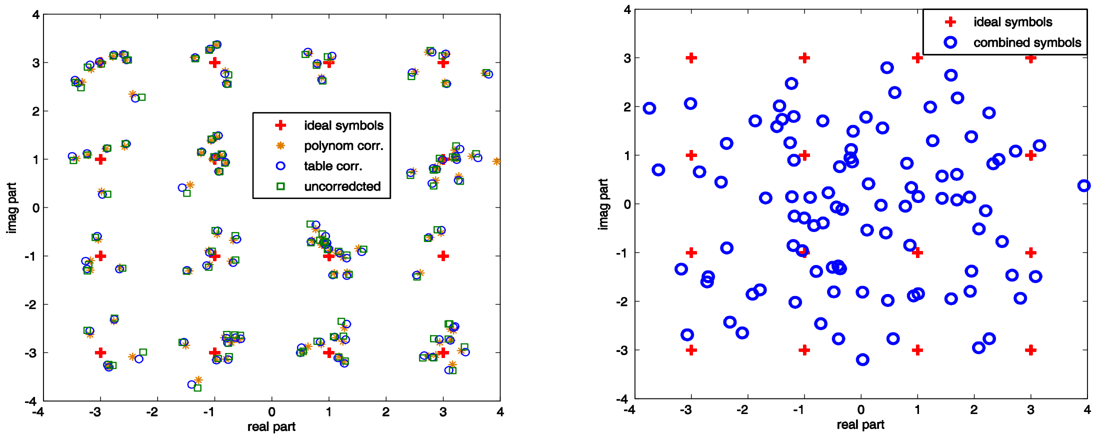

Figure 7: Constellation diagram with nearly ideal weights (left) and scrambled weights (right)

Table 3 summarizes the performance parameters of the two compensated and the unprocessed weights. It shows the remarkably small effect, when forward error correction of the weights is applied, on EVM in this scenario, although the maximum values of amplitude and phase error appear very large. However, the impact of errors in amplitude mapping is negligible, because the gain control circuit and normalization algorithm regulate the combined signal level. Thus, only the phase errors are responsible for the differences.

But as long as the angular mapping and hence, weighting error remains sufficiently small, the final SNR and EVM will not be seriously degraded after combining, since the response functions have an extremum at 0°.

Table 3: Forward error correction of the weights

	uncorrected = $[H]^{-1}$	table search	polynom inversion
complex weights	0.16 + j 0.18	0.12 + j 0.10	0.09 + j 0.14
	-0.34 + j 1.00	-0.33 + j 1.00	-0.3 + j 1.00
	0.40 + j 0.17	0.34 + j 0.09	0.32 + j 0.12
	-0.38 + j 0.02	-0.30 + j 0.03	-0.33 + j 0.01
amplitude mapping error [%]	31	1.9	0.86
angular mapping error [°]	6.0	1.0	0.2
resulting EVM [dB], NF=3dB	-16.7	-17	-17.9

5. Conclusion

With the proposed simulation framework the performance of a designed RF antenna combining system was successfully evaluated. For the considered DUT the most important measure EVM was presented and because all properties of the underlying circuits are taken into account by the transient simulator, the impact of the non-ideal mapping of the vector modulator could be studied. With two preliminary forward error correction methods a reduction of the EVM of 1.2 dB is obtained and it is concluded, that error correction of the weights can be omitted in a low-signal-level test-case. These results proof the applicability of the shown simulation framework, which will be further used to evaluate other analogue sub-systems in the course of MIMAX.

6. References

[1] R. Ludwig, P. Bretchko, G. Bogdanov, "*RF Circuit Design*", 2nd Edition, Prentice Hall, 2008

[2] G. Chrisikos, G. Paparisto, "*Conformance Metrics and Evaluation of HSDPA Systems with RF Impairments in Next Generation Wireless Standards*", in Proc. of 9th European Conference on Wireless Technology, 2006

[3] R. Eickhoff, F. Ellinger, U. Mayer, M. Wickert, I. Santamaria, R. Kraemer, L. Gonzalez, P. Sperandio and T. Theodosiou, "*MIMAX – Exploiting the maximum performance and minimum system costs of wireless MIMO systems*", in Proc. of 17th ICT Mobile and Wireless Summit, 2008

[4] R. Eickhoff, U. Mayer, F. Ellinger and C. Scheytt, "*High Performance and low power consuming MIMO systems using Adaptive Antenna Combining in the RF domain*", in Proc. of the ESA Microwave Technology and Techniques Workshop, 2008

[5] I. Santamaria, V. Elvira, J. Via, D. Ramirez, J. Perez, J. Ibanez, R. Eickhoff and F. Ellinger, "*Optimal MIMO Transmission Schemes with Adaptive Antenna Combining in the RF Path*", in Proc. of 16th European Signal Processing Conference, 2008.

[6] S. Woo, D. Lee, K. Kim, Y. Hur, C.-H. Lee, J. Laskar, "*Combined Effects of RF Impairments in the Future IEEE 802.11n WLAN Systems*", in Proc. of 61st Vehicular Technology Conference, 2005

[7] Cadence Design Systems, "*OCEAN Reference*", Product version 5.1.41, 2004

[8] IEEE-SA Standards Board, "High-speed Physical Layer in the 5 GHz Band," IEEE Std 802.11a-1999(R2003), Supplement to IEEE Std 802.11-1999, 2003

[9] R. Shafik, M. Rahman, A. Islam and N. Ashraf , "*On The Error Vector Magnitude As A Performance Metric And Comparative Analysis*", 2nd International Conference on Emerging Technologies, 2006

[10] N. Kriplani, S. Luniya and M. Steer, "*What Can Time-Domain Modeling do for RF Nonlinear Circuit Analysis?*", International Microwave Symposium, 2008

[11] T. Sickenberger and R. Winkler, "*Efficient Transient Noise Analysis in Circuit Simulation*", in Proceedings of Applied Mathematics and Mechanics, Vol.6, 2006